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Chapter 4: *Biologically inspired technologies for aerospace*

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ABSTRACT
Thru evolution over billions of years, nature addressed its challenges by trial and error and came up with inventions that work well and last. For its experiments nature employs principles of physics, mechanical engineering materials science, chemistry,, and many other fields of science and engineering. Nature inventions inspired human achievements in developing effective methods, materials, processes, structures, tools, mechanisms, algorithms, and systems. The field of technology that is based on inspiration of nature is known as Biomimetics and it offers enormous potential for many exciting future capabilities. There are numerous examples of biomimetic successes including making simple copies, as the use of fins for swimming. Others examples involved greater mimicking complexity including the mastery of flying that became possible only after the principles of aerodynamics were better understood. Some commercial implementations of biomimetics, including robotic toys, are increasingly appearing and behaving like living creatures. More substantial benefits of biomimetics include the development of prosthetics that closely mimic real limbs and sensory-enhancing microchips are used to interface them with the human brain to assist in hearing, seeing, and controlling instruments. The focus of this Chapter is on the aerospace related innovation that was inspired by nature and it covers various examples, the potentials and the challenges.

Keywords: Aerospace, Robotics, Biomimetics, EAP, Biologically inspired technology.

4.1 Introduction

Nature is a self-maintained experimental laboratory that is addressing its changing challenges through the trial and error process of evolution. In performing its experiments every field of science and engineering nature is involved with testing principles of physics, chemistry, mechanical engineering, materials science, mobility, control, sensors, and many others. Also, the process involves scaling from nano and macro, as in the case of bacteria and virus, to the macro and mega, including our life scale and the whales. The extinction of the dinosaurs may suggest that mega-scale land living animals are unsustainable form of life as opposed to mega-size sea creatures such as the whales. Observing and studying the capabilities of living creatures suggest numerous possibilities that can be adapted to solve and support human needs. Nature has always served as a model for mimicking and inspiration to humans in the efforts to improve the way we live. The subject of copying, imitating, and learning from biology is also known as Biomimetics and it represents the studies, imitation and inspiration of nature's methods, designs and processes [Bar-Cohen, 2005; Benyus, 1998; Schmitt, 2003; Vincent 2001; Vogel 2003]. Some of the capabilities were copied from nature while for others it served as an inspiring model. Flying was inspired by insects and birds using human developed capabilities, whereas the design and function of fins, which divers use, was copied from the legs of water creatures like the seal, goose and frog. Scientific approaches are helping humans understand nature's capabilities and the associated principles resulting in the development of effective tools, algorithms, approaches and other capabilities to benefit mankind. The ultimate goal of biomimetics may be the development of life-like robots that appear and function like humans. Efforts are currently underway to develop such robots and impressive capabilities have already been reported where humanlike robots can conduct conversation with limited vocabulary, respond to body and facial expressions as well as avoid obstacles while walking and others [Bar-Cohen and Hanson, 2009]. The focus of this chapter is on the biologically inspired innovation in aerospace.

In general, nature's materials and processes are far superior to man-made ones. The body of biological creatures is a laboratory that is processing chemicals acquired from the surrounding and produces energy, construction materials, multifunctional structures and waste [Mann, 1995; Nemat-Nasser et al. 2005]. Some of the capabilities of nature's materials include self replication, reconfigurability, self-healing, and balancing the content of various chemicals including the pH of its fluids as well as its temperature and pressure. Recognizing the advantages of these materials, for thousands of years, humans have used them as sources of food, clothing, comfort, construction and many other applications. These materials include fur, leather, honey, wax, milk and silk [Carlson et al. 2005]. The need to make these materials in any desired quantity led to developing approaches of enhancing their production from the related creatures as well as producing imitations. Many man-made materials are processed by heating and pressurizing, and this is in contrast to nature which uses ambient conditions. Materials, such as bone, collagen or silk are made inside the organism's body using nature friendly processes with minimal waste and the resulting strong materials are biodegradable and recyclable by nature.

Besides the multifunctional structures that makes up biological creatures they also have the capability to produce structures using materials that they make or pick up from the surrounding. The skeleton of animals' body is quite marvelous – it is able to support enormous physical actions even though it is not a rigid structure. Also, the produced structures (such as the nest and cocoon's shell and underground tunnels that gophers and rats build) are quite robust and support the structure's required function over the duration that it is needed. Often the size of a structure can be significantly larger than the species that builds it, as is the case of the spider's web. An example of a creature that has a highly impressive engineering skill is the beaver, which constructs dams as its habitat on water streams. The honeycomb is also an inspiring structure and it provides the bees a highly efficient packing configuration [Gordon, 1976]. Using the same configuration, the honeycomb is used to create aircraft structures benefiting from the low weight and high strength that is obtained. Even plants offer inspiration, where mimicking the adherence of seeds to animals' fur led to the invention of the Velcro and to numerous applications including clothing and electric-wires strapping.

The development of biomimetic systems and devices is supported by a growing number of biologically inspired technologies including artificial intelligence that mimic the control of biological systems [Amaral et al., 2004; Hecht-Nielsen, 2005; Serruya et al., 2002]. The invention of the wheel made the most profound impact on humans' life allowing traversing enormous distances and performing various tasks that otherwise would have been impossible to perform within the life time of a single person. While the wheel enabled enormous capabilities it has significant limitations when used for mobility in complex terrains that have obstacles. Obviously, legged creatures can operate in many such conditions and far superior ways than an automobile. Legged-robots are increasingly becoming an objective for the developers of robotic machines and these include even humanlike ones [Bar-Cohen and Breazeal, 2003; Bar-Cohen and Hanson, 2009]. Generally, the mobility of legged mechanisms currently is being done via motors. While motors have numerous advantages, since they require gear they are relatively heavy, structurally complex and have many potential points of failure. Advances in electroactive polymers (EAP), also known as artificial muscles, are expected to enable new possibilities for legged robotics with the potential of turning science fiction ideas into engineering applications [Bar-Cohen, 2004].

As a model for inspiration, it is important to remember that Nature solutions are driven by survivability of the fittest and these solutions are not necessarily optimal for the technical performance. Effectively, all organisms need to do is to survive long enough to reproduce. Living systems archive the evolved and accumulated information by coding it into the species' genes and passing the information from generation to generation through self replication.

There are great benefits to better understand how nature marvels work and how to adapt them in human made mechanisms. These include such capabilities as:

- The dragonfly flight performance in air flying backwards, as well as stopping and starting flight in air using their relatively small body [Huang and Sun, 2007].
- The toughness of spider silk and its ability to produce the silk at room temperatures and pressure conditions [Trotter, 2000].
- The navigation capability of the Monarch butterfly migration of great distances and reaching targeted locations at which as an individual it has never been before. This information is coded in their genes of its quite small body size [Sauman et al., 2005].
- The strength of seashells that is quite enormous even though it is made of calcium carbonate that effectively is a soft material also known as chalk [Yang, 1995].
- Our ability to identify people whom we have not seen for many years and that have chanced appearance enormously.

The above list is only a small number of examples and covering them all can be an enormous task and the challenge to adapt them can even be much more complex. This Chapter examines various examples that are relevant to aerospace.

4.2 Biologically inspired or independent human innovation

Nature and its biological systems have been on Earth many billions of years before humans reached the level of intelligence that was enough to start making their own tools. In the effort of humans to become domestic and minimize the dependence on luck and their harvesting of the surrounding resources, they started seeking to improve the way they live. Observing nature was part of their daily life and it inspired them with ideas of how to acquire and handle food, how to protect themselves and their resources as well as many other things that were essential to their way of life.

One may wonder how inspiring on humans' innovation have been the various creatures that lived in their neighborhoods. The presence of spiders in humans' habitats should have had some inspiring role on making such things as wires, ropes, nets, sieves, screens and woven fabrics. One cannot avoid seeing the similarity of a spider web and the fishing net or the screen in screen-doors or even the kitchen sieve as shown in **Figure 1**. Beside the sieve that may have been inspired by seeing creatures that are widely present in human habitats, another application to food handling is the tong and it has been probably inspired by the beak of birds as shown in **Figure 2**.

Figure 1: The spider web has been probably the inspiring design for numerous human made tools. From top left to right: spider web, net, and screen door. Bottom: kitchen sieve.

Figure 2: The tong may have been likely inspired by the beak of birds and the way they grab food.

From another angle on the subject of biomimetics one may wonder if all the inventions and tools that are commonly used by humans were inspired by nature or, maybe, it was just a coincident that the solution ended having similar features. An example may include the honeycomb that looks very much the same in the nature and the technology versions. In the case of the bees, the honeybee serves as a highly efficient packing container for their off-springs and food storage when their eggs hatch. On the other hand, the honeybee in aircraft structures provides a highly efficient space filler of various parts that are lightweight and have great strength. Also, it is interesting to notice that many of the mammals are 4 legged creatures and most of our furniture, such as chairs and tables, are supported by 4 legs (see an illustration of this point in **Figure 3)**. It is hard to believe that all the human made solutions were pure inventions of individuals who ignored what they have seen in nature and came up with them on their own.

Roboticists are well aware that making robots operate with legs significantly increases their capability and mobility in complex terrains. In recent years, there are increasing efforts to create legged robots for various applications including space and military and examples are shown in **Figure 4** and **Figure 5**.

Figure 3: One may wonder if the 4-legs of most animals have been an inspiring model for the furniture like chairs and tables.

Figure 4: Military application of legged robotics.

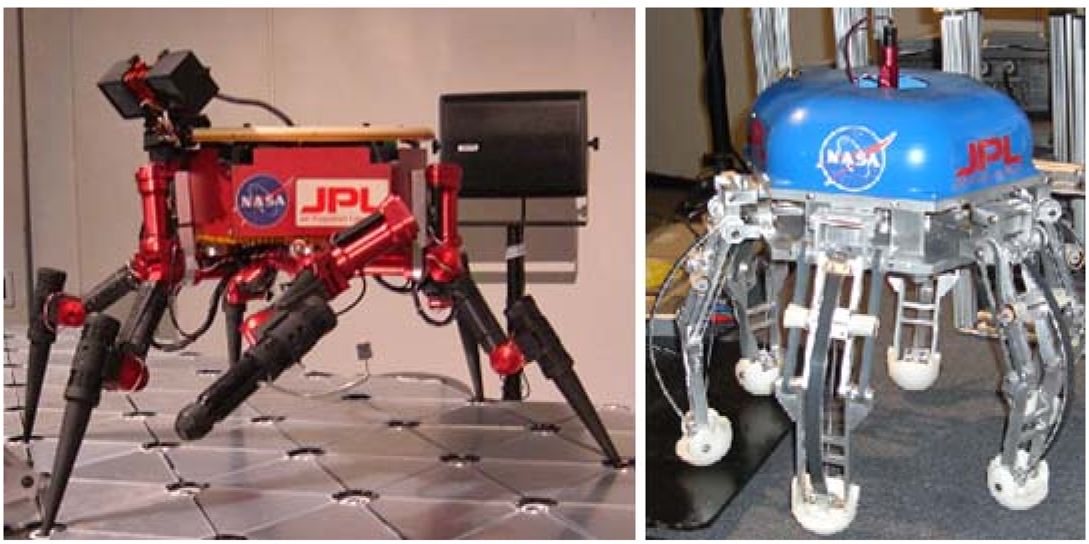

Figure 5: Examples of legged robots that were developed at JPL for space application. Future robots may climb mountains and perform lifelike functions. Courtesy of JPL/Caltech/NASA.

4.3 Nature as a source of innovation in aerospace

The field of aerospace as we know it today was inspired by the insects and birds ability to fly using human developed technology (**Figure 6**). The enormously huge number of flying capable species suggests that nature has extensively "experimented" with aerodynamics and has been quite successful. Birds are able to maneuver in flight with quite amazing capabilities as well as while flying carry prey that can be quite large and heavy compared to their body. They can even catch preys while flying including, for example, a running rabbit or swimming fish and they are able to predict their path intersection with the hunted creature. This capability to hunt while the hunter and the hunted creatures are both moving fast (running, flying, or swimming) is increasingly the capability of military weapons allowing tanks to destroy a moving vehicle while they are both moving fast. Also, missiles are used to hit enemy fighter aircraft or other missiles by tracking the moving target and either adjust the direction in flight or aim at the moment of launch.

Figure 6: Inspired by nature and aerodynamic principles lead to the flying capabilities of aircraft as the supersonic passenger plane, the Concord, which is shown on the right. Photographed by the author at the Boeing Aerospace Museum, Seattle, WA.

Another form of biologically inspired flight is under consideration for potential future NASA mission at the Ohio Aerospace Institute (**Figure 7**). This study is taking into consideration that flying on Mars is much more difficult than on Earth due to the low air pressure and therefore it is necessary to operate within a very low Reynolds number regime. In addition to this restriction one needs to take into account the practical size limitations of a vehicle that can be deployed from Earth. An entomopter vehicle was recently proposed that uses biomimetic configuration [http://www.niac.usra.edu/files/studies/abstracts/448Colozza.pdf] and circulation control techniques to achieve substantially higher lift. The concept is based on the use of a micro-scale vortex at the wing's leading edge as determined in 1994 by Charles Ellington of the University of Cambridge [Scott, 1999]. Taking advantage of the lower gravity on Mars one may be able to develop an insect inspired flying machine at a size of a meter. For power the wing will be covered with flexible solar cells throughout the structure (see bottom left of **Figure 7**). Under a DARPA sponsored study researchers at the Georgia Tech Research Institute have preliminary confirmed that this concept may be feasible for operation on Mars possibly allowing the vehicle to take off, fly slowly or hover, and land.

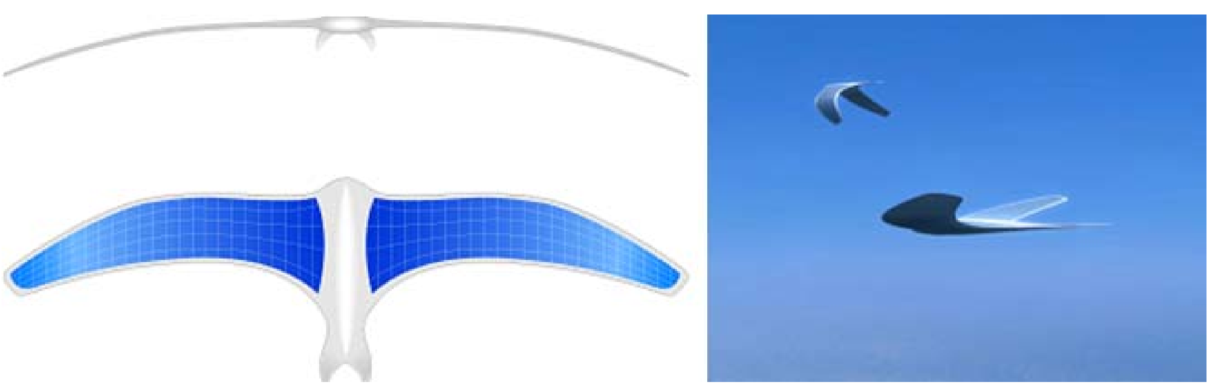

Figure 7: A flying mechanism that emulates the bird was proposed for planetary exploration missions. Courtesy of Anthony Colozza, Ohio Aerospace Institute.

Wagging the tail is leading form of propulsion in water and many of sea creatures are able to develop significant speeds of swimming. Inspired by this propulsion method and using balloon design, with helium for operation in air, researchers at EMPA, Switzerland, Duebendorf, Switzerland, in collaboration with the Institute of Mechanical Systems of ETH, Zürich, Switzerland, are currently developing such a flying vehicle [Michel et al., 2007]. The project objective is to use electroactive polymers emulating muscles to produce a lighter-than-air vehicles. In the first phase, a blimp was developed that has its fins bent by EAP based actuators to the left and right allowing steering the blimp. The goal is to develop a novel bionic propelled blimp that is operated like a fish with tail wagging capability. For this purpose, fluid dynamics, structural mechanics, and flight performance are explored with systematic experimental studies. The commercial application of this technology is the development of larger blimps for use in transportation, observation and reconnaissance, as well as stratospheric platforms.

Figure 8: Photographic view of the EAP activated blimp (the black strips are dielectric elastomer EAP). Photographed by the author at the SPIE's 2008 EAPAD Conference.

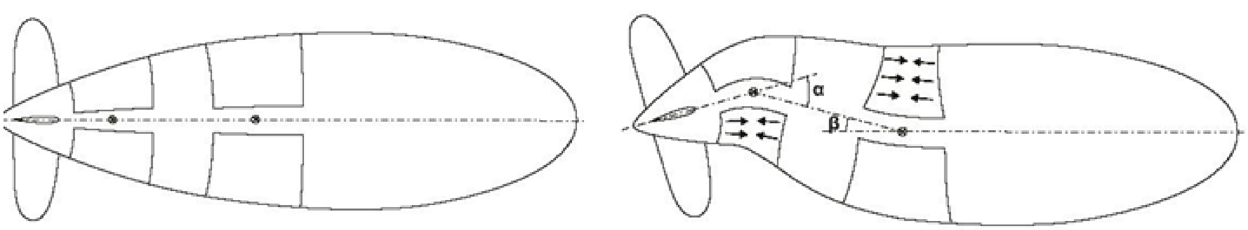

Figure 9: A graphic view of the envisioned EAP activated blimp that is propelled like a fish. Courtesy of Silvain Michel, EMPA - Materials Science & Technology, Duebendorf, Switzerland.

The dragonfly is an incredible flying insect that can maneuver in air at relatively high speeds. Its capability has been under studies for many years in an effort to adapt or inspire aeronautic innovation and solution to existing problems [Huang and Sun, 2007]. The dragonfly adjusts the effects of high G on its body during its flight and rapidly maneuvers using liquid-filled sacs that surround its cardiac system. This method has inspired the Swiss company, Life Support Systems, to develop an anti-G suit that allows pilots to fly at high mach speeds with significantly lower effects on their ability to stay coherent. The developed liquid-filled suit is called "Libelle," which means in German dragonfly [http://www.lssag.ch/website%2003%2014.html]. Tests of the Libelle suit have shown promise as far as the advantages over the pneumatic (compressed air) anti-G suits and they are being tested at various air forces.

Plants use many method of dispersing their seeds including being blown in the wind and being shaped with aerodynamic configuration to enable the largest traveled distance. Thus, the plant species reduce the danger of crowding of the specific type of plant in the same local area that may cause competing over the same resources as well as being subjected to the same environmental risks that possible endanger the survival. There are various aerodynamic configurations of seeds and an example is shown in **Figure 10** where the seed of the tree Tipuana tipu (about 6.5-cm long) has a wing that propels it in the wind. It is also interesting to mention the tropical Asian climbing gourd Alsomitra macrocarpa that is a tree with a relatively large seed having a 13-cm wingspan. The flight of the latter seed resembles a boomerang and it is capable of gliding in wide circles through the rain forest. One may see quite a similarity of these seeds and helicopter blades and it is most likely have been an inspiring design for many aerodynamic parts of aircraft and other human made flying machines.

Another aerospace related area that is benefiting from biomimetics is the design and development of potential alternatives for planetary landing of rovers and landers on planets with atmospheres (such as Mars and Venus). Adapting such designs may offer better alternative for the use of a parachute on Mars and possibly a better ability to steer the landing hardware at selected sites. Some of the issues that are being studied include the determination of the appropriate vehicle size, mass distribution and platform shape to assure stable autorotation and scalability from operation on Earth to performance on Mars.

Figure 10: Seeds of the Tipuana tipu, which has aerodynamic shape for dispersion by the wind.

The tumbleweed is another plant that offered an inspiring design for planetary mobility that is powered by wind [Wilson et al., 2006]. Generally, winds are blown throughout Mars and they provide an attractive source of mobilizing a rover by mimicking tumbleweed. As shown in **Figure 11**, the tumbleweed has inspired a futuristic lander that could one day be used as a vehicle for mobility on Mars for traversing great distances with minimal use of power. At NASA Langley, using three-dimensional dynamic modeling and simulations [Shouthard et at., 2007] has shown that dispersion and exploration of Mars with Tumbleweed rovers is feasible. A likely mission scenario involves an organized search for geologically interesting features using a group of rovers with heterogeneous sensor packages. A tumbleweed rover can potentially travel longer distances and gain access to areas such as valleys and chasms that previously were inaccessible. Varying the location of the mass imbalance is one of the methods currently under consideration for controlling the motion of wind-blown tumbleweed like rover.

Figure 11: The tumbleweed (left) offered an inspiration for a futuristic design of a Mars rover (right). The right hand figure is used under a courtesy of NASA. http://smart-machines.blogspot.com/2007/04/nasas-tumbleweed-inspired-rovers-for.html

4.4 Biologically inspired mechanisms and systems

Making aerospace structures can benefit greatly if they could be made of materials that have nature's characteristics of self-healing, self replication, reconfigurability, chemical balance, durability and multi-functionality. The advantages of biological and botanical materials were well recognized by humans and were used for many applications [Carlson et al. 2005]. Learning how to process biologically inspired materials can make our choices greater and improve our ability to create recyclable materials that can better protect the environment. Mimicking nature materials will also benefit humans in many other ways including the development of more life-like prosthetics, where increasingly artificial parts such as hips, teeth, structural support of bones and others are being produced. There are also many mechanisms that were biologically inspired including:

Ground penetration as a gopher and a crab – Since 1997, the author, members of his Group at JPL, and engineers from Cybersonics, Inc., have been involved with research and development of sampling techniques for future in-situ exploration of planets in the Universe. The developed techniques are mostly driven by piezoelectric actuators and the Ultrasonic/Sonic Driller/Corer (USDC) in particular [Bao et al., 2003; Bar-Cohen et al., 2005a; Bar-Cohen et al., 2005b]. The general configuration of the USDC allows it to penetrate sub-surfaces to a depth that is no longer than the length of the bit since the other parts are larger in diameter. In order to reach greater depth with less restrictions of the depth, two models of deep drills were conceived that were inspired by the gopher and sand-crab [Bar-Cohen et al., 2005b]. A piezoelectric actuator induces vibrations that impacts the medium that is in contact and the mechanism that consists of a bit with a diameter which is the same or larger than the actuator. The device that emulates the biological gopher is lowered into the produced borehole, cores the medium, breaks and holds the core, and finally the core is extracted onto the surface. This Ultrasonic/Sonic device can be lowered and raised from the ground surface via cable as shown in **Figure 12**. This device was called the Ultrasonic/Sonic Gopher and it was designed analogously to the biological gopher that digs into the ground. It removes the loose soil out of the underground tunnel that it forms, bringing it to the surface and resumes the process to reach great depths. The Ultrasonic/Sonic Gopher was developed to the level of a prototype and demonstrated at Mount Hood and in Antarctica to perform its intended function. Further, the Ultrasonic/Sonic Crab design emulates the sand crab, which shakes its body to penetrate sand on beaches. This device uses mechanical vibrations on the front surface of the end-effector to penetrate media that consist of loose soil, sand, or particulates. The Ultrasonic/Sonic Crab was not produced yet however its implementation is not expected to pose major technical challenges.

Pumping mechanisms: Nature uses many pumping mechanisms that have inspired human made mechanisms. The most common pumps are peristaltic pumping, where liquids are squeezed in the required direction. The lungs pump air in tidal process using the diaphragm that allows us to breath. Pumping via valves and chambers that change volume is found in human and animal hearts, where the chambers expand and contract to allow the flow of the blood. Just like in mechanical pumps, the flow of the blood is critically dependent on the action of the valves in the heart.

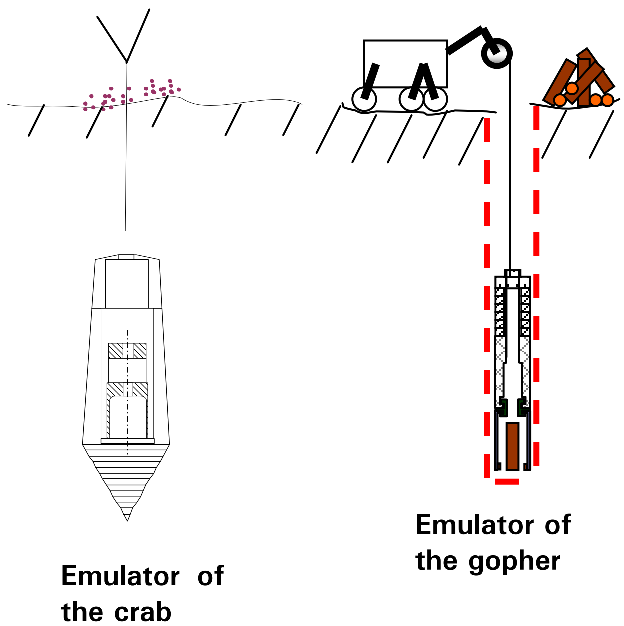

Figure 12: Biologically inspired ground penetrators: Left - the Ultrasonic/Sonic Crab; and Right – the Ultrasonic/Sonic Gopher.

Artificial muscles: Muscles, which are both compliant and linear in behavior [Full and Meijer, 2004], are the actuators of biological systems allowing all our physical movements. Emulating the characteristics of muscles is important allowing for making robots that function with lifelike performance. The actuators that are closest to emulate natural muscles are the electroactive polymers (EAP), which have emerged in recent years and gained the name "artificial muscles" [Bar-Cohen., 2004]. There are many types of EAP materials known today and most of them have emerged in the 1990s. Unfortunately, they are still not generating sufficient forces to perform significant tasks such as lifting heavy objects. In order to help advancing the field rapidly, the author initiated and organized in March 1999 the first annual international EAP Actuators and Devices (EAPAD) Conference [Bar-Cohen, 1999]. This conference is held annually by the technical society SPIE as part of its Smart Structures and Materials Symposium. At the opening of the 1st Conference, he posed a challenge to the worldwide scientists and engineers to develop a robotic arm that is actuated by artificial muscles to win an armwrestling match against a human opponent. The icon of the challenge can be seen in **Figure 13** illustrating the wrestling of human with robotic arm driven by artificial muscles.

Figure 13: The icon of the armwrestling challenge for artificial muscles match against human.

On March 7, 2005, the author organized the first arm-wrestling match with human (17-year old high school female student) as part of the EAP-in-Action Session of the SPIE's EAPAD Conference. In this contest, three EAP actuated robotic arms participated and the girl won against all three (see **Figure 14**). Following this match in the 2nd contest, rather than wrestling with a human opponent, the contest consisted of measuring the arms performance and comparing the results. A measuring fixture was used to gauge the speed and pulling force. To establish a baseline for comparison, the capability of the above student was measured first and then three participating robotic arms were tested. This 2nd Artificial Muscles Armwrestling Contest was held on Feb. 27, 2006, and the results have shown two orders of magnitude lower performance of the arms compared to the student. In a future conference, once advances in developing EAP actuated arms lead to sufficiently high force, a professional wrestler will be invited for another human/machine wrestling match.

Figure 14: The robotic arm driven by artificial muscles, made by Virginia Tech students, is being prepared for the 2005 match against the human opponent.

Inchworm motors: Another form of actuation that was biologically inspired is the movement of the biologic inchworm, which is a caterpillar of a group of moths called *Geomeridae*. Emulating the mobility mechanism of this larva or caterpillar led to the development of high precision motors and linear actuators that are known as inchworms. The forces that are generated by the commercial types of inchworms can reach over 30-Newtons with zero-backlash and high stability. As opposed to biological muscles, the piezoelectric actuated inchworms are involved with zero-power dissipation when holding position. Inchworm mechanisms have many configurations with the basic principle of using two brakes and an extender. These motors perform cyclic steps where the first brake clamps onto the shaft and the extender pushes the second brake forward. Clamping the second break and stretching the extender allows making the first step that is then repeated as many times as needed. Inchworm motors were used already in the Telesat (NASA mission) in the mid-1980s allowing for high precision articulation in the range of nanometers.

Bio-Sensors: It is well recognized that sensors are a critical part of any system allowing it to monitor its functions and respond to the operation conditions as needed. Sensors emulate the senses in biological creatures, which provide inputs to the central nervous system about the environment around and within their body and the muscles are commanded to action after analysis of the received information [Hughes, 1999]. Biological sensory systems are extremely sensitive and limited only by quantum effects [Bialek, 1987; Bar-Cohen, 2005]. Sensors are widely used and it is not possible to imagine effective operation of any system without them. Pressure, temperature, optical and acoustical sensors are widely in use and continuously being improved in terms of their sensing capability while reducing their size and consumed power. The eye is emulated by the camera, the whiskers of rodents are emulated with collision avoidance sensor, and acoustic detectors imitate the sonar in bats. Similar to the ability of our body to monitor the temperature and keep it within healthy acceptable limits, our homes, offices, and other enclosed areas have environment control that allow us to operate at comfortable temperature levels. One of the recent studies related to applications in aerospace include the development of an artificial fly unmanned aircraft system with combined hearing and vision for navigation to inaccessible locations. This is an on-going research at the University of Maryland that is funded by the US Air Force Office of Scientific Research (AFOSR) [http://www.af.mil/news/story.asp?id=123125017]. In this study, the capability of a pair of mechanically-coupled ears that are separated by only 500 microns is being investigated while seeking to incorporate advances in microelectronics and other system-on-a-chip capabilities. This study is focused on the understanding, modeling and emulation of the ability of flies to combine hearing and vision at micro-scale levels as means of rapid flying and response.

Artificial Intelligence (AI): Controlling the operation of systems in automatic way can be limited if a simple software with known answers to any of the possibilities is used. Increasingly, systems are being made "smart' using artificial intelligence where the control algorithms are emulating nature [Musallam et al., 2004; Mussa-Ivaldi, 2000]. The field of AI is providing important tools for making automatic and robotic mechanisms with capabilities such as knowledge capture, representation and reasoning, reasoning under uncertainty, planning, vision, face and feature tracking, language processing, mapping and navigation, natural language processing, and machine learning [Bar-Cohen and Breazeal, 2003; Kurzweil, 1999; Luger, 2001]. Generally, AI is a branch of computer science that studies the computational requirements for such tasks as perception, reasoning, and learning, to allow the development of systems that perform these capabilities [Russell and Norvig, 2003]. Through improvement of the understanding of human cognition [Hecht-Nielsen, 2005] scientists are able to understand the requirements for intelligence in general, and develop artifacts such as intelligent devices, autonomous agents, and systems that cooperate with humans to enhance their abilities. AI researchers are using models that are inspired by the computational capability of the brain and explaining them in terms of higher-level psychological constructs such as plans and goals.

4.5 Robotics as beneficiary of biomimetic technologies

Creating robots that mimic the shape and performance of biological creatures has always been a highly desirable engineering objective [Bar-Cohen and Breazeal, 2003; Bar-Cohen and Hanson, 2009]. The term robot refers to a biomimetic machine with humanlike features and functions that consists of electro-mechanical mechanisms. Also, it suggests a machine that is capable of manipulating objects and sensing its environment as well as equipped with a certain degree of intelligence. Searching the Internet for the word robot brings numerous links related to research and development projects that are involved with robots. Manipulator arms that are fixed to a single position and perform such tasks as painting and assembly are part of many production lines including the manufacturing of cars. Rovers that have locomotion with wheels or legs are already being made autonomous and are able to perform quite sophisticated tasks. These include the Mars Rovers that have operating since 2003 on Mars in terrains that are unknown and they are capable of avoiding obstacles while conducting various tasks in support of the exploration of this planet.

The entertainment and toy industries have been greatly benefited from advancement in this technology. Toys that emulate the appearance and movement of such creatures as frogs, fish, dogs and even babies are now part of many stores. The higher end robots and toys are becoming increasingly sophisticated, allowing them to walk and even converse with humans as well as appear converse with human using a limited vocabulary at the level of hundreds of words. Some of the robots can be operated autonomously or can be remotely reprogrammed to change the characteristic behavior. An example of a robot that expresses and reacts to human expressions facially and verbally is the Kismet that was developed at MIT [Bar-Cohen and Breazeal, 2003; Breazeal, 2004]. As this technology evolves it is becoming more likely that in the future, humanlike robots may be part of our daily life operating at our homes and offices and doing work that currently is done by humans. Beside the benefits of this technology there is a need for awareness of the potential risks that these robots may pose due to errors or even malicious intents.

Industry is increasingly benefited from advancement in robotics and automation that are biologically inspired [Bar-Cohen, 2000; Bar-Cohen and Breazeal, 2003]. Crawlers with the equivalence of legs as well as various manipulation devices are increasingly being used to perform a variety of nondestructive evaluation (NDE) tasks. At JPL, a multifunctional automated crawling system (MACS) was developed to allow rapid scanning of aircraft structures in field conditions (**Figure 15**). The MACS consists of two legs for the mobility on structures with one of the legs designed also to rotate. This crawler performs scanning by "walking" on aircraft fuselages while adhering to the surface via suction cups and is capable walk upside down on such structures. The mobility on structures is critically dependent on the capability of the legs to have controlled adherence and alternative forms that were reported include the use of magnetic wheels and electrostatic field. Using magnetic wheels, the author and his coinvestigator [Bar-Cohen and Joffe, 1997] conceived a rover that can operate on ships and submarines using magnetic wheels. Another legged robot is the JPL's STAR that has 4 legs and can perform multiple functions (**Figure 5**), including grabbing objects as well as climbing rocks with the aid of the ultrasonic/sonic anchor on each of the legs [Bar-Cohen, 1999; Bar-Cohen and Sherrit, 2003; and Badescu et al. 2004]. This anchor provides the ability to "hang-on" rocks via mechanism that requires a relatively low axial force to drill into the rocks as well as extract the bit in a reverse action. The JPL's legged robots are developed for potential operation in future planetary mission, where a Lemur class robot will be able to autonomously negotiate its way through unknown terrain that is filled with obstacles (**Figure 16**).

Figure 15: MACS crawling on a wall using suction cups on two simulated legs.

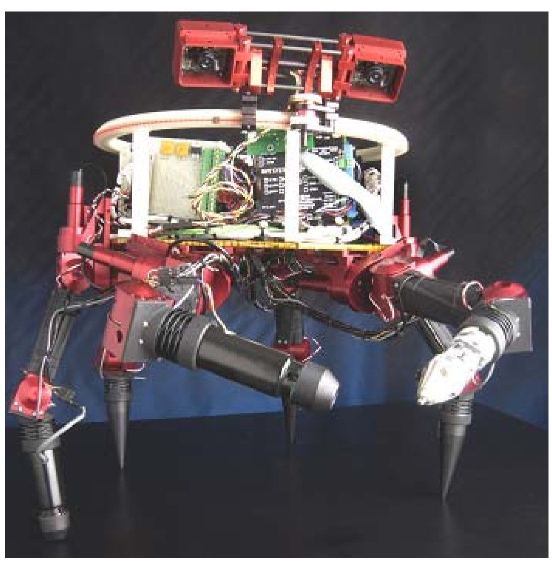

Figure 16: JPL's Lemur, 6-legged robots, in a staged operation (Courtesy of Brett Kennedy, JPL/NASA)

4.6 Summary – the challenges and potential development

The evolution of nature over billions of years led to highly effective and reasonably power efficient biological mechanisms, which are appropriate for the intended tasks and that last [Petr, 1996]. The ongoing evolution eliminates failed solutions and often leads to the extinction of specific species that do not sustain the changing conditions. As it evolves, nature archived its solutions in the genes of creatures that make up the terrestrial life around us. Imitating nature's mechanisms offers enormous potentials for the improvement of our life and the tools we use. With the capability of our today's science and technology we are significantly more capable of employing, extracting, copying and adapting nature's inventions.

Nature offers a model for us as humans in our efforts to address our needs as well as a source for inspiring many human-made devices, processes and mechanisms. By studying nature from the angle of seeking ideas for biologically inspired technologies many applications can result including stronger fiber, multifunctional materials, improved drugs, superior robots, and many others. Preventing the loss of Nature's solutions that managed to survive at least till we understand them well is an important aspect of biomimetics where we need to assure that species are not extinct since they may harbor inventions that we have not appreciated yet. We can learn manufacturing techniques from animals and plants such as the use of sunlight and simple production of compounds with no prolusion, biodegradable fibers, ceramics, plastics, and various chemicals. One can envision the emergence of extremely strong fibers that are woven as the spider does, and ceramics that are shatterproof emulating the pearl or possibly seashells. Besides providing models, nature can serve as a guide to determine the appropriateness of our innovations in terms of durability, performance, and compatibility.

The inspiration of nature on aerospace is expected to continue growing and to enable technology improvements with impacts on every aspect of our lives. Miniature flying devices that are as small as a fly or less with speeds and performance of the dragon fly are still a challenge to mimic. However, some of the inspired future capabilities may be considered science-fiction in today's terms, but as we improve our understanding of nature and develop better capabilities this may become a reality that is closer than we think.

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4.8 References

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